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COMPANIONS TO NEARBY STARS WITH ASTROMETRIC ACCELERATION. II. [1]

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ABSTRACT

Hipparcos astrometric binaries were observed with the NICI adaptive optics system at Gemini-S, completing the work of Paper I (Tokovinin et al. 2012). Among the 65 F, G, K dwarfs within 67 pc of the Sun studied here, we resolve 18 new sub-arcsecond companions, re-measure 7 known astrometric pairs, and establish the physical nature of yet another three wider companions. The 107 astrometric binaries targeted at Gemini so far have 38 resolved companions with separations under 3″. Modeling shows that bright enough companions with separations on the order of an arcsecond can perturb the *Hipparcos* astrometry when they are not accounted for in the data reduction. However, the resulting bias of parallax and proper motion is generally below formal errors and such companions cannot produce fake acceleration. This work contributes to the multiplicity statistics of nearby dwarfs by bridging the gap between spectroscopic and visual binaries and by providing estimates of periods and mass ratios for many astrometric binaries.

Subject headings: stars: binaries

1. INTRODUCTION

This work completes the study of astrometric binaries started in Tokovinin et al. (2012, Paper I). Many new companions to solar-mass nearby dwarf stars were inferred from their accelerated motion, either detected directly as $\dot{\mu}$ binaries by the *Hipparcos* mission (Perryman & ESA 1997; van Leeuwen 2007), or by comparing short- and long-term proper motion ($\Delta\mu$ binaries, see Makarov & Kaplan 2005, MK05). Only a fraction of those objects have computed visual and/or spectroscopic orbits; the yet unknown periods of most acceleration binaries range from a few to a thousand years. By resolving "dark" astrometric companions directly, we get much tighter estimates of their periods (from the projected separations) and masses (from the apparent magnitude).

There are 343 stars with accelerated proper motion (PM) among dwarfs of spectral types F and G located within 67 pc of the Sun (the FG-67pc sample). In Paper I, 51 of those stars were observed with adaptive optics (AO), resolving for the first time 17 sub-arcsecond companions and 7 wider companions. The "success rate" was slightly less than expected from the binary statistics. However, it was established that some acceleration solutions in the *Hipparcos* catalog are spurious. Some astrometric companions could be white dwarfs (WDs), too faint to be resolved. These two considerations bring the resolution rate in better agreement with the expectations.

Here we report AO observations of 65 targets. They are selected among dwarfs within 67 pc with color index $0.5 < V - I < 1.0$ which corresponds to spectral types from F5V to K2V. Seven of them were resolved previously and are re-observed here for confirmation and for detection of orbital motion. Out of the 5 tentative resolutions in Paper I, we confirm three and refute two. To our knowledge, the remaining 58 stars were observed with AO for the first time. We resolved 18 sub-arcsecond companions and three wider pairs. The observations are presented in Section 2. In Section 3 the influence of faint, unrecognized companions on *Hipparcos* astrometry is investigated. Then in Section 4 we discuss the statistics of the combined sample of 107 astrometric binaries observed at Gemini.

2. OBSERVATIONS AND RESULTS

The Near-Infrared Coronagraphic Imager (NICI) on the Gemini South telescope is an 85-element curvature adaptive optics (AO) instrument based on natural guide stars (Toomey & Ftaclas 2003; Chun et al. 2008). As in Paper I, we used NICI in normal (non-coronagraphic) mode, with simultaneous imaging at two wavelengths. The two detectors of NICI have 1024^2 pixels of 18 mas (milliarcseconds) size, covering a square field of 18″. To avoid saturation, we selected narrow-band filters with central wavelengths of 2.272 μm and 1.587 μm for the red and blue imaging channels.

The program started in Paper I was continued by observing 18 more stars from the original list in 2012A, in the period from March to May. The observations of another 47 Hipparcos astrometric binaries were taken in queue mode in the period from September 2 to December 24, 2012 using 8 h of allocated time. The observing procedure and data reduction are the same as in Paper I and in Tokovinin, Hartung, & Hayward (2010). The images of each target at five dither positions were median-combined after removing bad pixels, subtracting the median sky frame, dividing by a flat field, and accounting for the dither by shifting back the images to co-align the source with the first frame.

The total of 29 companions with separations from 0.″05 to 9.″2 were resolved, 18 of those for the first time. All resolutions appear secure (Figure 1). The reality of de-

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[1] Based on observations obtained at the Gemini Observatory (Programs GS-2011B-Q69 and GS-20012B-Q-71).

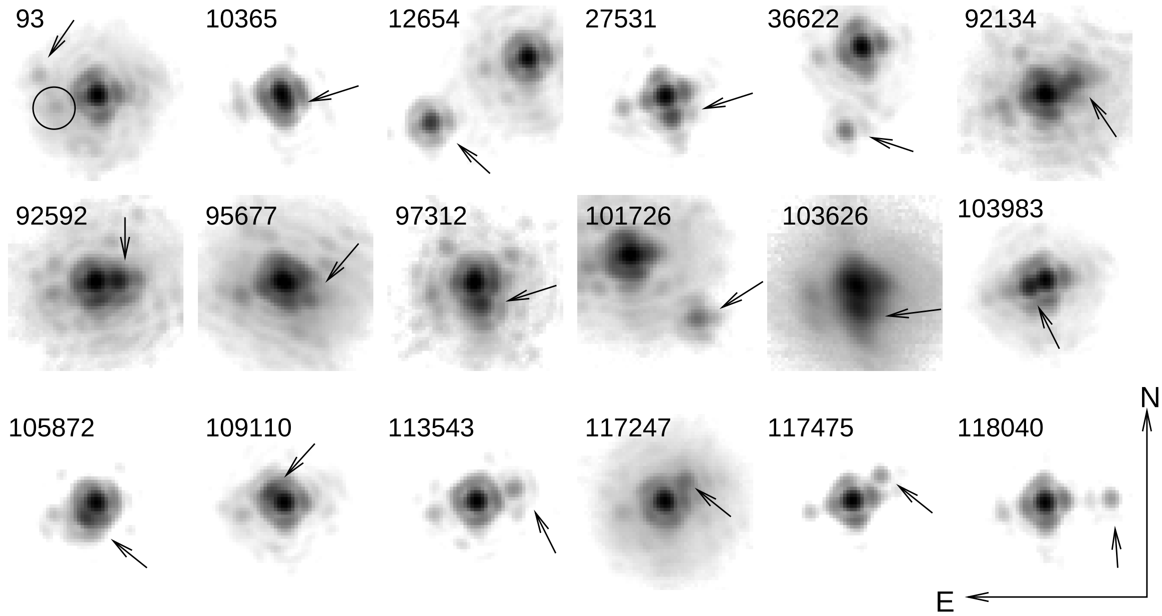

FIG. 1.— Images of 18 newly resolved sub-arcsecond companions in the red channel (2.272 μm), marked by the HIP numbers. Negative logarithmic intensity scale (white is 0.003 of maximum intensity), each fragment is 50x50 pixels (0.9″). The "ghost" companion to the left of each target (circled in the first image) is a reflex in the NICI optics.

tections is checked by "blinking" the red and blue images and by comparing with other stars. Some companions are better seen in the blue images where the speckle structure is less prominent and point sources are sharper. The faint "ghost" with $\Delta m \sim 4.3$ at $0.''24$ to the left of each star is produced by the NICI optics.

The limiting magnitude for companion detection was determined from the intensity fluctuations in annular zones, as in Paper I. The detection depth depends on the AO compensation quality which was variable, reflecting the seeing variation. The median detection depth in the red channel is $\Delta m = 5.^{m}1$ at $0.''27$ and $\Delta m = 7.^{m}4$ at $0.''90$. These formally computed detection limits are only indicative because actual detections depend on companion's location and on details of the speckle structure.

Table 1 lists the relative astrometry and photometry of resolved pairs measured independently on the red and blue images. Previously resolved pairs are marked by R in the last column, the uncertain measures are marked by colons. For well-resolved ($\rho > 0.''5$) companions the measure is obtained by fitting the shifted and scaled image of the main companion which serves as Point Spread Function (PSF). For closer companions we used a blind deconvolution. It starts from the initial estimate of the binary parameters (separation ρ, position angle θ, and intensity ratio) derived by "clicking" on the companion in the image display. The halo of the primary companion at $(\rho, \theta + 90°)$ is subtracted from the intensity of the secondary peak. The first PSF estimate is then obtained by de-convolving the image from the binary. At the first iteration, the PSF at distances beyond 0.75ρ is replaced by its azimuthal average. This "synthetic" PSF is then used for the least-squares fitting of the binary parameters. The fitting is done in the Fourier space at spatial frequencies from $0.2 f_c$ to the cutoff f_c, thus neglecting large-scale intensity variations in the halo and fitting only fine structure – the PSF core and speckles around it. The process is repeated iteratively (new PSF from the binary, new binary parameters, etc.) until convergence, when the rms deviation between the image and its model does not decrease anymore. The reliability is evaluated qualitatively by the PSF that should have no traces of the companion. Blind deconvolution works very well in most cases, but it does not produce reliable results for the faintest or closest companions near the detection limit. In such cases the difference between measures in the red and blue channels informs us of their quality.

The relative position of components in pixels is transformed to the position on the sky using the nominal NICI parameters: the pixel scale of 18.0 mas and the known offset in position angle.

The list of targets observed in 2012 is given in Table 2. It is similar to the Table 2 of Paper 1 and provides rounded values of the parallax $p_{\rm HIP}$, accelerations $\Delta\mu$ and $\dot{\mu}$ from (Makarov & Kaplan 2005), radial velocity (RV) variation if it is variable, mostly from the Geneva-Copenhagen Survey (GCS) of Nordström et al. (2004). Then follow the estimates of the primary mass M_1 and mass ratio $q = M_2/M_1$ derived from known distance, combined K_s magnitudes from 2MASS (Cutri et al. 2003), magnitude differences in the red channel measured here, and the standard relations of Henry & McCarthy (1993). The values of q, separation ρ, and order-of-magnitude period estimate P^* are given only for resolved pairs. The following two columns of Table 2 list the detection limits at 15 and 50 pixel separations ($0.''27$ and $0.''90$) in the red channel (see above). Notes on individual objects are assembled at the end of Table 2. For some objects, preliminary spectroscopic orbits were determined at Center for Astrophysics (CfA) in Harvard.[2]

We re-observed all 5 binaries for which Paper I reports tentative resolutions. Three (HIP 21778, 22387, 25148) are confirmed here. Of the two unresolved pairs, HIP 12425 is likely single (no acceleration in van Leeuwen 2007), while HIP 114880 could have closed in, considering its short estimated period and variable

[2] Latham, D. W. 2012, private communication.

RV.

The case of HIP 12654 is perplexing. A companion so bright and so separated (0.″6) should have been resolved by *Hipparcos*, unless the pair was much closer 21 years ago. If its semi-major orbital axis is half the actual separation, 0.″3, the orbital period should be 60 yr, so a periastron passage in an eccentric orbit could have happened during the *Hipparcos* mission. This assumption is supported by $\Delta\mu = (-13.0, +14.4)$ mas yr^{-1}, directed at 264° (away from the companion) and amounting to 0.″4 over 21 yr. A few other bright and well-resolved companions were found in Paper I, e.g. HIP 24336 and 21079. The effect of binary companions *detectable* but not actually *detected* by *Hipparcos* is studied in the next Section.

3. EFFECT OF FAINT COMPANIONS ON THE HIPPARCOS ASTROMETRY

The *Hipparcos* satellite obtained the astrometric parameters of the target stars through one-dimensional scans at different angles while the spacecraft was spinning. The star light was modulated using a grid of slits placed in the focal plane with a slit width of 0.″46 and a period of s = 1.″2074. The positions of the stars in scan direction, the *abscissae*, were determined by fitting the first and second Fourier harmonics of the grid period to the photon counts. The relative amplitude and phase of the two harmonics, μ and ν, were calibrated for single stars; they depend slightly on the field position and star color. Significant deviations from these calibrations were used to detect resolved binaries with the limiting magnitude difference of $\Delta Hp \lesssim 4^m$. For the remaining unresolved stars, including all stars in this program, the number of free parameters was reduced to three by fixing μ and ν to their calibrated values. Thus, the photon counts as a function of the scan phase x (in radians) were fitted by a sum of two sine terms (equation 5.5, p. 54, in van Leeuwen et al. 1997)

$$I(x) = r_1 + r_2 \cos(x + r_3) + \mu r_2 \cos 2(x + r_3 + \nu) \quad (1)$$

with fixed μ and ν and three free parameters r_i.

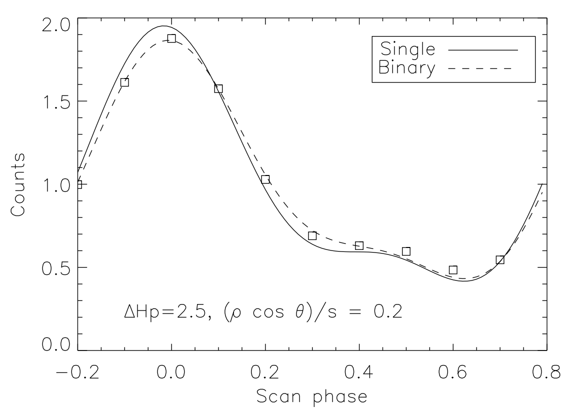

FIG. 2.— Photon counts vs. scan phase (fraction of the grid period) for a single star (full line) and a binary (dashed line). The squares denote a single-star scan model fitted to the scan of a binary.

Figure 2 shows a representative scan of a single star with typical parameters $r_2/r_1 = 0.7$, $\mu = 0.37$, and $\nu = 10°$, assuming $r_1 = 1$ in equation 1. The effect of a binary companion with $\Delta Hp = 2.5^m$ and 0.″24 separation in the scan direction is shown by the dashed line. Such a companion would actually be recognized by *Hipparcos*, but a star with a fainter, un-detected companion would be treated as single and fitted by the calibrated 3-parameter model. Such a fit (squares in Figure 2) results in the decreased modulation amplitude r_2 and some shift of the abscissa (change of r_3). To investigate the shift of the abscissa caused by undetected companions, we fitted single-star models to simulated scans of binaries, with uniform weights. The shift of the abscissa (i.e. the star position in the scan direction) Δv can be represented by two sine terms,

$$\Delta v \approx s\alpha\,(0.103 \sin y + 0.028 \sin 2y), \quad (2)$$

where $\alpha = 10^{-0.4\Delta Hp}$ is the flux ratio of the companion in the *Hipparcos* bandpass and $y = 2\pi(\rho\cos\theta)/s$ is the combination of the binary separation ρ, its angle θ relative to the scan direction, and the grid period s. The maximum effect of $\Delta v = 0.11\alpha s$ is reached when $\rho\cos\theta = 0.2s =$ 0.″24, e.g $\Delta v = 1.3$ mas for a companion with $\Delta Hp = 5$. When the projected separation is $s/2$, the abscissa is not affected, the companion only decreases the modulation. The coefficients of the model (2) depend slightly on the weights used to fit the scans. If the weight is inversely proportional to the flux (as would be the case of Poisson noise and negligible background), the coefficients become 0.114 and 0.022.

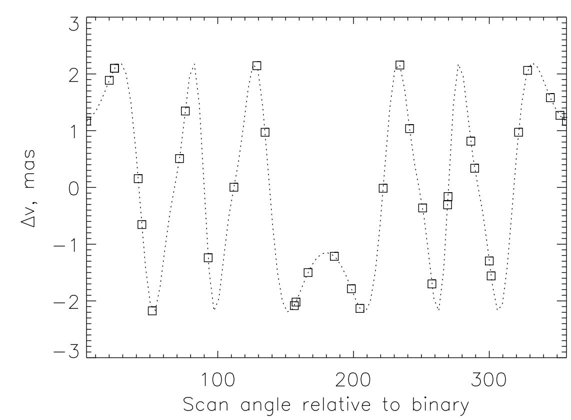

FIG. 3.— Shifts of great-circle abscissae Δv caused by the companion of HIP 21079 (1.″622, 23.4°) assuming $\Delta Hp = 4.5$, as a function of the scanning angle. The dotted line is equation 2, the squares correspond to the 36 orbits (i.e. scans) used in the astrometric solution for this star.

The five astrometric parameters of single stars (α, δ, μ_α, μ_δ, π) are derived by fitting the measured abscissae. An undetected companion changes the abscisssae and therefore is expected to affect the astrometry. Can these abscissae shifts explain the $\Delta\mu$ or $\dot\mu$ for some wide binaries resolved by NICI but treated as single stars by *Hipparcos*? We study three case examples to answer this question.

Case 1: A companion to HIP 21079 was found in Paper I at ρ = 1.″622, position angle 23.4°, and $\Delta K = 1.62$. The Hipparcos Intermediate Astrometry Data (HIAD) for this star were retrieved from the ESA archive.[3] For

[3] `http://www.rssd.esa.int/index.php?project=HIPPARCOS\discretionary{`

the 36 *Hipparcos* orbits processed by the FAST consortium, the abscissae were modified by adding the Δv terms from equation 2. We use the standard relations for dwarf stars to estimate $\Delta V = 4.5$ and set $\Delta Hp \approx \Delta V$ (relative photometry of this pair at SOAR in February 2013 gave $\Delta V = 4.6 \pm 0.1$). The scanning direction for each orbit was calculated from the derivatives $\partial v/\partial\alpha*$ and $\partial v/\partial\delta$ given in the HIAD. Figure 3 shows the resulting Δv, with an amplitude of ± 2.2 mas. The rms abscissa residuals caused only by the effect of the companion, i.e. ignoring any other measurement errors, are 1.4 mas. When we fit five astrometric parameters to the modified abscissae by unweighted least-squares, the residuals decrease only slightly, to 1.2 mas (the actual rms abscissa residual is 5.1 mas). The parallax does not change, the PM changes by $(0.3, -0.4)$ mas yr^{-1}. The effect of the companion is therefore too small to explain $\Delta\mu = 5$ mas yr^{-1} for this star. As we see in Figure 3, the abscissa shifts caused by the companion are quasi-random, they oscillate in function of the scan angle. These shifts do not correlate significantly with any of the five astrometric parameters and, therefore, cannot be "absorbed" by modifying the single-star astrometric solution. The estimated period of this binary, 570 yr (Paper I), makes it unlikely that the companion moved substantially in 21 yr since the *Hipparcos* mission.

Case 2: For HIP 12654 ($\rho = 0\farcs60$, position angle 125.0°, $\Delta K = 1.03$) we did the same analysis as above. If its companion is a normal main sequence dwarf we expect $\Delta Hp \approx 1.8$. Here, the rms shifts of abscissae caused by the companion are 12.4 mas before adjusting the astrometric solution and 11.0 mas after, while the actual rms residual of the FAST abscissae is 4.1 mas. The effect of the companion is too strong compared to the actual residuals. However, it is likely that at the time of the *Hipparcos* mission (1991.25) the companion of HIP 12654 was too close to be resolved, while causing the real PM effect of $\Delta\mu = 19$ mas yr^{-1}.

The alternative reductions by the NDAC consortium give very similar results for both HIP 21079 and HIP 12654, and the new catalog of van Leeuwen (2007) does not differ significantly from the original reductions.

Case 3: HIP 103260 is the known binary I 18 with a companion of $\Delta V = 3.2$ according to the WDS (Mason et al. 2001). This companion was measured in Paper I at $3\farcs975$ and 351.3°, but was not recognized by *Hipparcos*, which gives an acceleration solution with $\dot{\mu} = 7$ mas yr^{-2}. The 26 orbits covering this star are not distributed in time uniformly and tend towards the end of the mission, creating correlation between PM and acceleration in the least-squares fitting of the abscissae. The resulting ill-conditioned acceleration solution amplifies the noise, including the abscissa shifts caused by the companion (5.0 mas rms). This effect has been discussed in Paper I; spurious acceleration of 11 mas yr^{-2} was obtained by fitting a 7-parameter solution to the companion-induced Δv of this binary. The unrecognized companion also biases the parallax by +2.8 mas in the 5-parameter solution and by +1.6 mas in the 7-parameter acceleration solution. Analogous distortion of *Hipparcos* parallaxes by *close* companions was evidenced by Shatskii & Tokovinin (1998). In this case the shifts $\Delta v(\theta)$ resemble a sine wave and correlate stronger with the astrometric parameters.

In summary, faint undetected binary companions typically modify the measured abscissae by a few mas. As these "errors" are quasi-random, their effect on the standard 5-parameter astrometric solution is usually below its formal errors, except for cases like HIP 103260 (Case 3) where its parallax or PM can be slightly biased or when an ill-conditioned acceleration solution amplifies all (measurement and companion-induced) errors.

4. STATISTICS AND DISCUSSION

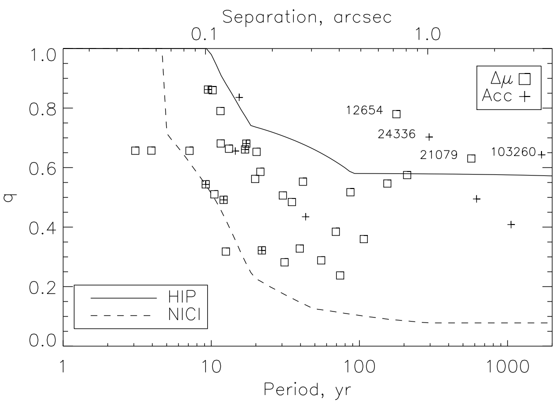

Fig. 4.— Detection limits of NICI and Hipparcos in the (period, mass ratio) parameter space and resolved astrometric binaries from this work and Paper I. Four pairs with long periods and large q are labeled by their HIP numbers.

Paper I evoked published speckle interferometry to study the statistics of resolved astrometric binaries in a sample of 99 objects. Here we use only the NICI data (which go deeper than speckle) and discuss the merged sample of 107 objects observed at Gemini. The estimated periods P^* and mass ratios q of these pairs are plotted in Figure 4. The full and dashed lines depict the typical detection limits of *Hipparcos* and NICI, respectively, at a distance of 50 pc. The two pairs with the shortest periods around 3 yr (HIP 10365 and 109110) are formally beyond the limit. There are 38 companions with $\rho < 3''$ ($P^* \lesssim 2000$ yr) – 20 from Paper I and 18 from this work.[4]

The detection rate of $38/107 = 35.5 \pm 6\%$ is significantly below the 55% rate predicted for NICI by the simulations of Paper I. As in Paper I, we correct the observed rate to 45% by accounting for 10% of known binaries that were excluded from the NICI program and for 10% of WD companions, but the result is still too low. Remember that the simulations are sensitive to the assumed binary statistics and contain some simplifications. The observed detection rate is uncertain because of hierarchical multiples (some resolutions are actually tertiary companions where the inner closer sub-systems produce the acceleration). For these two resasons we are not concerned about the remaining disagreement between observed and simulated detection rates. If we ignore $\dot{\mu}$ binaries and consider only 83 $\Delta\mu$ binaries where 30 companions with $P^* \leq 100$ yr are resolved, the observed rate is $36.1 \pm 6.5\%$.

Note the striking absence of resolved companions with $P^* > 100$ yr and $q < 0.4$ in the lower-right corner of

[4] Although the resolution of HIP 114880 is not confirmed here, we consider it real because of the variable RV.

Figure 4, despite their easy detectability with NICI (one such pair was resolved with speckle, see Figure 3b of Paper I). There is no doubt that low-mass companions with $P > 100$ yr are abundant (Raghavan et al. 2010). However, at such long periods the $\sim$100 yr time baseline of *Tycho-2* samples only a fraction of the orbit and the *Tycho-2* PM no longer represents the center-of-mass motion, as assumed in our simulations described in Paper I. Therefore the $\Delta\mu$ (the difference between *Hipparcos* and *Tycho-2* PMs) is reduced (both catalogs measure nearly the same) and the chances of discovering $\Delta\mu$ are reduced. If most $\Delta\mu$ binaries indeed have periods shorter than 100 yr, their number decreases by $\sim$18% compared to our simulations (see the cumulative curve in Figure 4a of Paper I).

The NICI companions with $P^* > 100$ yr and relatively large estimated q (labeled points in the upper-right part of Figure 4) were not resolved by *Hipparcos* and were treated as single stars. They are too wide to cause real $\dot{\mu}$. Our modeling shows that in most cases such companions do not produce a substantial effect on astrometry, unless the companion-induced errors are amplified in ill-conditioned acceleration solutions (HIP 103260). Either those $\dot{\mu}$ are spurious, or we deal with triple systems where the acceleration is produced by inner, unresolved sub-systems (HIP 16853 and 109443 have variable RV). On the other hand, HIP 12654 and 21079 have standard 5-parameter solutions, their $\Delta\mu$ is most likely real and caused by their wide companions.

Some secondary companions could be close binaries, like in HIP 11072 (Tokovinin 2013). In this case they are redder than single dwarfs of equal luminosity, making their direct resolution by *Hipparcos* and NICI more difficult, while the large combined mass produces detectable astrometric accelerations. Presence of such dark and massive companions in the binary population improves the agreement of simulations with reality (Paper I).

Low-mass companions also produce color-dependent shifts of stellar positions. The companion of HIP 21079 with $\Delta K = 1.9$ and $\rho = 1\farcs6$ displaces the image centroid in the K band by $0\farcs25$ in the direction of 23°. The difference of equatorial coordinates of this star between 2MASS and *Hipparcos* (both for the epoch and equinox J2000.0) implies a displacement of $0\farcs14$ at 30° angle and matches the companion's angle. However, considering systematic errors, uncertainties of the 2MASS astrometry ($\sim$60 mas) and the PM errors multiplied by the difference of epochs, this effect could not be accepted as a companion detection if the latter were not directly resolved with NICI. In conclusion, very precise simultaneous astrometry at different wavelengths can reveal a companion's presence and can be used for their detection.

During few nights allocated to this project we surveyed 107 acceleration binaries out of few thousand reported in MK05, or about 1/3 of 343 such objects in the FG-67pc sample. Therefore, no major changes of our statistical results are expected and as the NICI instrument is no longer available, we consider this work as completed.

The observations reported here and in Paper I explore nearby dwarf binaries in the regime difficult to study by other methods: the periods are mostly too long for RV coverage, the companions are too faint to be resolved at visible wavelengths. Astrometric detection of such binaries by *Hipparcos* is therefore an excellent opportunity to bridge the gap between spectroscopy and imaging. Improved characterization of astrometric binaries and understanding some caveats of *Hipparcos* astrometry are the main results of this study. In a broader perspective, it contributes to the multiplicity statistics of nearby dwarfs, many of which are targeted by exo-planet programs.

We thank Fredrik Rantakyro and Peter Pessev (Gemini) for careful observations of our program stars, David Latham for sharing unpublished data from the CfA survey, Valeri Makarov for discussion of companion's impact on *Hipparcos* astrometry, and Wolfgang Brandner for general remarks on binary statistics and methodics. This work used the SIMBAD service operated by Centre des Données Stellaires (Strasbourg, France), bibliographic references from the Astrophysics Data System maintained by SAO/NASA, data products of the Two Micron All-Sky Survey (2MASS) and the Washington Double Star Catalog maintained at USNO. Gemini telescopes are operated by the Association of Universities for Research in Astronomy, Inc., under a cooperative agreement with the NSF on behalf of the Gemini partnership: the National Science Foundation (United States), the Science and Technology Facilities Council (United Kingdom), the National Research Council (Canada), CONICYT (Chile), the Australian Research Council (Australia), Ministério da Ciência e Tecnologia (Brazil) and Ministerio de Ciencia, Tecnología e Innovación Productiva (Argentina).

Facilities: Gemini:South (NICI)

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van Leeuwen, F. 2007, A&A, 474, 653

TABLE 1
Measures of resolved companions

HIP	Date	Red 2.272 μm			Blue 1.587 μm			Rem
		P.A. (deg)	Sep. (arcsec)	Δm (mag)	P.A. (deg)	Sep. (arcsec)	Δm (mag)	
93	2012.8317	71.8	0.317	4.34	72.4	0.323	4.34	
1103	2012.7361	302.0	6.193	4.47	302.5	6.204	4.63	
6273	2012.6707	113.6	0.254	2.39	113.5	0.254	2.71	R
6712	2012.7362	28.8	0.100	0.84	29.9	0.101	0.97	R
10365	2012.6704	198.4	0.056	0.83	198.2	0.054	0.47	:
11072	2012.6706	339.3	0.345	1.78	339.9	0.344	1.53	R
12654	2012.7362	123.8	0.610	1.09	123.8	0.610	1.24	
21778	2012.6706	189.4	0.148	2.98	188.5	0.143	3.42	R
22387	2012.6706	58.8	0.140	4.19	62.6	0.143	3.38	R:
25148	2012.6707	209.4	0.065	1.21	213.0	0.059	0.80	R:
27531	2012.7363	196.2	0.118	1.54	196.3	0.116	1.83	
36622	2012.9745	169.2	0.445	2.44	169.1	0.446	2.71	
88595	2012.2379	293.0	6.609	5.52	293.1	6.624	7.15	
92134	2012.2380	294.0	0.166	2.20	295.3	0.165	2.29	AB
92134	2012.2380	292.5	9.164	3.98	292.6	9.155	4.20	AC
92592	2012.2380	271.4	0.121	1.04	271.6	0.124	1.28	
95677	2012.2380	232.8	0.161	3.65	234.2	0.156	3.39	:
97312	2012.4132	194.1	0.118	1.61	190.7	0.112	1.61	
101726	2012.2381	226.9	0.483	2.95	226.8	0.482	3.19	
103626	2012.3449	188.1	0.123	0.94	188.3	0.121	1.07	
103983	2012.8313	110.0	0.087	0.60	111.6	0.087	0.71	
105872	2012.8996	149.2	0.097	1.70	138.1	0.087	1.61	
107731	2012.3450	307.3	5.587	3.59	307.3	5.561	4.21	
109110	2012.8315	48.5	0.082	1.74	46.9	0.080	1.73	:
113543	2012.8316	287.5	0.214	2.92	287.2	0.208	3.05	
117247	2012.8317	312.4	0.151	2.94	309.8	0.150	2.51	
117258	2012.8316	20.0	0.227	1.96	19.7	0.226	2.24	R
117475	2012.8315	310.5	0.196	3.27	309.5	0.196	3.72	
118040	2012.8315	273.3	0.347	3.17	273.3	0.347	3.41	

TABLE 2
Summary data on observed astrometric binaries

HIP	p_{HIP} (mas)	$\Delta\mu$ (mas yr^{-1})	$\dot{\mu}$ (mas yr^{-2})	ΔRV (km s^{-1})	M_1 ($M_\odot$)	q	ρ (arcsec)	P^* (yr)	Δm_{15} (mag)	Δm_{50} (mag)
93	16	6	0	1.2	1.08	0.24	0.317	74.1	5.26	7.15
290	15	13	0	1.3	1.19				4.97	7.32
305	21	12	10	0.0	1.10				5.39	7.80
359	17	15	0	-	0.85				4.97	6.18
1103	15	8	11	-	1.20	0.25	6.193	6654.3	5.57	7.69
1274	15	14	7	-	1.01				5.53	7.40
1573	22	13	0	1.3	1.12				5.36	7.75
1976	21	13	20	5.1	1.07				5.36	7.80
3578	25	7	15	2.4	0.94				5.29	7.81
4668	15	10	0	-	0.93				5.30	7.12
4981	17	6	0	-	0.84				5.52	7.46
6273	30	19	0	2.2	0.92	0.56	0.254	19.8	5.04	7.86
6712	18	16	25	0.8	0.94	0.82	0.100	9.3	5.28	7.70
7961	20	11	0	1.7	1.17				5.34	7.91
8674	19	14	0	0.0	0.87				5.64	7.85
10365	19	7	0	-	0.94	0.66	0.047	3.1	5.38	7.67
11072	45	0	19	0.0	1.22	0.66	0.343	14.5	1.95	5.98
12425	15	0	17	0.0	0.99				5.55	7.93
12654	16	19	0	0.0	0.84	0.78	0.614	177.7	3.16	4.32
17184	20	10	28	0.0	0.93				4.94	7.41
19248	28	12	5	SB	0.92				5.48	7.71
21778	23	15	11	1.6	0.98	0.49	0.141	12.1	5.65	7.79
22387	18	9	8	2.3	1.06	0.19	0.142	18.3	5.51	7.90
23641	24	9	33	4.1	0.79				5.42	7.49
25148	15	5	0	3.7	0.97	0.75	0.065	6.8	5.23	7.38
27531	21	14	0	1.0	0.72	0.68	0.118	11.6	5.16	7.64
30509	17	8	0	2.2	1.09				5.41	7.47
34212	17	7	23	4.3	1.13				5.13	7.12
34961	18	9	12	0.0	0.88				5.38	7.17
36622	20	8	0	0.0	0.86	0.52	0.445	86.9	2.74	7.29
38134	19	11	6	5.6	1.05				5.38	7.66
88595	17	0	9	-	0.97				5.54	7.47
91215	15	0	8	0.0	1.19				5.39	7.64
92134	17	14	0	0.0	0.96	0.59	0.158	21.4	5.38	7.49
92592	19	7	0	-	0.87	0.79	0.115	11.5	5.04	7.49
94370	18	5	0	0.8	1.00				5.27	7.55
94668	16	12	34	2.0	1.01				5.46	7.50
95677	17	10	6	0.0	1.18	0.54	0.096	9.2	5.38	7.55
95696	15	7	19	1.6	1.14				5.45	7.73
96754	17	0	8	0.0	1.20				5.08	7.67
97312	15	18	18	0.0	1.08	0.68	0.123	17.2	5.31	7.53
98108	16	0	11	2.3	1.13				5.54	7.63
99708	15	0	12	-	1.01				5.47	7.16
100934	18	18	8	0.8	0.96				4.61	5.22
101726	26	8	0	0.0	0.85	0.38	0.475	69.3	2.82	8.20
102130	18	7	0	4.8	1.04				5.42	7.48
103626	16	0	15	-	0.83	0.84	0.116	15.4	4.45	6.87
103983	15	9	0	0.2	0.96	0.86	0.087	10.2	4.95	7.19
105872	15	10	0	-	0.91	0.66	0.097	13.2	5.49	7.38
105879	15	9	7	2.3	1.33				4.32	6.92
106560	24	6	5	1.7	0.91				5.09	6.41
107239	16	8	0	-	0.92				4.94	7.17
107731	15	10	12	-	1.03	0.34	5.587	5831.4	4.40	6.00
108589	17	7	0	8.5	1.00				5.59	7.86
109110	28	17	0	SB	0.93	0.66	0.082	3.9	5.21	7.65
109122	16	15	22	4.0	1.25				5.46	7.79
110340	19	7	0	0.0	0.90				5.58	7.40
112396	15	7	0	-	0.86				5.80	7.41
113543	17	11	0	SB	1.13	0.51	0.205	30.4	5.26	7.71
114040	16	14	11	5.7	1.02				4.92	6.60
114880	16	8	0	2.5	1.08				4.35	6.43
117247	27	8	0	-	0.80	0.32	0.151	12.5	5.55	6.60
117258	25	11	0	1.4	1.02	0.62	0.227	20.1	4.49	7.30
117475	15	5	0	-	0.99	0.33	0.197	39.6	5.65	7.75
118040	19	13	0	-	0.81	0.31	0.347	75.4	5.19	7.62

Note. —
HIP 93: *first resolution*. Spectroscopic binary with a long period acording to GCS and CfA.
HIP 305: *unresolved*. RV=const, $\Delta\mu = 12$ mas yr^{-1}, possibly single.
HIP 1103: *likely triple system*. We confirm the companion at $6''.17$, 303° from 2MASS as physical, i.e. common proper motion (CPM). The 2MASS gives the companion's $J-K$ color too blue for a dwarf; the erroneous photometry is possibly caused by the proximity of the bright component. This pair is too wide to cause the acceleration, so the system is likely triple. The star was on the GCS survey but has no RV data. It is a ROSAT X-ray source.

TABLE 2
(Continued)

Note. —
HIP 3578: *unresolved* with NICI and speckle despite acceleration and variable RV. SIMBAD gives the wrong spectral type F0IV; it is a 1.0 solar-mass dwarf with $V-K=1.63$.
HIP 4981: *unresolved*, possibly single: small $\Delta\mu$, no RV data.
HIP 6273: retrograde motion by 4° since its first resolution at Gemini on 2011.84. Also measured at SOAR with speckle on 2012.93. Goldin & Makarov (2006) propose two orbits with periods around 9 yr, the semi-major axis should then be 0.″15, so the system is near apastron. It will close down and move faster in the coming years.
HIP 6712: direct motion by 20° since first resolution at Gemini on 2011.84 at 9°, 0.″10, at constant separation. Estimated period about 10 yr. Also measured at SOAR on 2012.92 at 39.0°, 0.″0998. The small RV amplitude suggests an orbit in the plane of the sky.
HIP 7961: *unresolved astrometric and spectroscopic binary.* The visual companion BUP 24 at 85″is likely optical because it is not recovered in 2MASS and has only one measure in the WDS.
HIP 8674: unresolved. Possibly single with a small $\Delta\mu = 12$ mas yr^{-1} and constant RV.
HIP 10365: *first resolution.* A short 3-yr period is expected but no RV data exist. Strangely, *Hipparcos* measured no acceleration, only $\Delta\mu = 7$ mas yr^{-1}. The pair is below the formal detection limit, but it is resolved securely.
HIP 11072: astrometric binary with large acceleration where the massive companion B is in fact a close pair of M-dwarfs (Tokovinin 2013). The image of the primary is strongly saturated. For this reason the measurements reported in Table 1 are obtained by PSF-fitting at radii from 5 to 10 pixels to avoid the center. The relative photometry is uncertain.
HIP 12425: tentative resolution on 2011.84 at 78°, 0.″34, $\Delta K = 3.8$ is not confirmed here, with new good-quality images. The star has a constant RV, so it could be single. In fact, the 17 mas yr^{-2} acceleration is not confirmed by van Leeuwen (2007).
HIP 12654: the 0.″6 pair with $\Delta K = 1.1$ is obvious and should have been resolved both by visual observers and by *Hipparcos.* Yet it is not listed as binary in the WDS (Mason et al. 2001) and no indications of previous resolution are found in the literature. The declination of −79° may have something to do with the missed companion as the southern sky is less well surveyed for binaries.
HIP 19248: *triple system* consisting of a 2.5-d spectroscopic pair and a 0.″1 tertiary companion discovered in (Tokovinin et al. 2006) and previously revealed by the *Hipparcos* acceleration and RV trend. It is not resolved here, apparently it closed in.
HIP 21778: direct motion by 16° since first resolution at Gemini on 2011.80 (176°, 0.″165), closing down. Estimated period 15 yr.
HIP 22387: retrograde motion by 5° since resolution on 2011.78 at 65°, 0.″16. Period about 20 yr. The measurements are uncertain because of the large Δm. The "blue" color of the companion ($\Delta H < \Delta K$) is caused by measurement errors.
HIP 25148: the tentative resolution of this close pair at Gemini on 2011.70 at 195°, 0.″06 is confirmed here with 25° of direct motion. Again, the $\Delta H < \Delta K$ likely results from the measurement errors.
HIP 27531: *first resolution,* $P^* = 12$ yr.
HIP 34212: the image seems elongated at 45°, *partially resolved?* A large RV amplitude and large acceleration hint at a short period.
HIP 36622: *first resolution,* $P^* = 85$ yr.
HIP 38134: this metal-poor astrometric and spectroscopic binary is not resolved here.
HIP 88595: the faint and red companion at 6.″6, 293° is likely optical. This is a very crowded field in the direction of the Galactic center. We see another companion at 10.8″, but only in the red channel. The acceleration might be spurious.
HIP 91195: likely spurious acceleration, constant RV.
HIP 92134: *triple system.* The $\Delta\mu$ binary AB is resolved. The wider companion C (9.″16, 292.5°, $\Delta K = 3.98$) is confirmed as CPM by 2MASS (8.″9, 292.8°), it also has a $J-K$ color corresponding to its estimated mass. The measurement of AC by PSF fitting is not strongly affected by the faint B-companion.
HIP 92592: *triple system.* The inner astrometric binary is resolved here, the CPM companion at 146″ is found by Tokovinin & Lépine (2012).
HIP 94370: unresolved. $\Delta\mu$ and long-period spectroscopic binary according to CfA.
HIP 94668: variable RV and large acceleration, close binary?
HIP 95677: *first resolution,* $P^* = 9$ yr.
HIP 96754: this double-lined binary with $q = 0.822$ according to GCS is apparently too close for resolution with NICI.
HIP 97312: *first resolution,* $P^* = 17$ yr, but constant RV according to GCS.
HIP 98108: acceleration and spectroscopic binary, unresolved here.
HIP 99708: no RV data, the acceleration could be spurious. Elongated image?
HIP 100934: data of low quality.
HIP 101726: *first resolution,* $P^* = 70$ yr, constant RV. This binary was not resolved by speckle interferometry, possibly because the companion is too faint in the visible. It is an X-ray source and a "PMS star" according to SIMBAD.
HIP 102130: unresolved. Spectroscopic binary according to both GCS and CfA.
HIP 103626: *first resolution* of the close pair with acceleration. No RV data. This is an X-ray source.
HIP 103983: *first resolution,* $P^* = 10$ yr. The pair can be followed with speckle because of small Δm. It is on the Keck exo-planet search program.
HIP 105872: *first resolution.*
HIP 105879: unresolved. Variable RV. The companion HJ 5267 AB at 5″ is listed in the WDS with one measurement and is not seen here. It should be considered spurious.
HIP 106560: unresolved. Astrometric and spectroscopic binary. High proper motion, low metallicity.
HIP 107731: the companion at 5.″6, 307° is physical, confirmed by 2MASS at 5.″3, 309° and hence CPM (the PM of A is 0.″37 per year). The companion's photometry in 2MASS, $J-K=-0.15$ and $\Delta K = 2.48$, is uncertain and likely distorted by the proximity of A. The photometry in Table 1 is reliable (PSF-fitting) and implies a red companion color (Δm of 3.6 and 4.2 in the read and blue channels respectively). This wide companion cannot explain the acceleration.
HIP 108589: unresolved. With only a small $\Delta\mu = 7$ mas yr^{-1} it can be single, despite two discordant RV measures in the GCS.
HIP 109110: the spectroscopic binary with a preliminary 13-yr period (CfA) and expected semi-major axis of 0.″19 is *tentatively resolved here for the first time* at 0.″07 with $\Delta K = 1.7$. Strangely, it was not resolved previously by speckle and by AO (Metchev & Hillenbrandt 2009). This is a young BY Dra variable NT Aqr and an X-ray source.
HIP 110340: unresolved. With $\Delta\mu = 7$ mas yr^{-1} and constant RV, it might be single.
HIP 113543: *first resolution* at 0.″21 is secure and hints at a 30-yr period, but the preliminary SB orbit (CfA) has 9-yr period and corresponds to 0.″09 semi-major axis. Follow-up observations are needed.
HIP 114880: tentatively resolved on 2011.85 at 147°, 0.″10, $\Delta K = 2.5$, but not confirmed here. As the RV is variable, we suppose that the pair was actually resolved last year, but has closed in.
HIP 117247: *first resolution* at 0.″15, $P^* = 12$ yr.
HIP 117258: resolved on 2011.85 and found here at nearly same position, despite $P^* = 20$ yr. Seen in projection?
HIP 117475: *first resolution* at 0.″20, $\Delta K = 3.2$. The companion is seen very clearly, of nearly the same magnitude and separation as the NICI ghost. No RV data.
HIP 118040: *first resolution*, $P^* = 75$ yr.